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SENSOR PERFORMANCE AND THE VEHICLE

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Abstract

In this tutorial paper, remote imaging sensors such as airborne photography, infrared scanners, electro-optical sensors, television, and radar are discussed in terms of how their performance is affected by the aerospace vehicle in which they are carried. Imaging sensor performance is discussed in terms of such criteria as resolution, contrast rendition, dynamic range, signal-to-noise ratio, sensitivity, geometric fidelity, general appearance of results, reliability, and data usefulness. How the aerospace vehicle, carrying the sensor, affects the above criteria is discussed in terms of vehicle altitude (or distance from target), temperature at the sensor, moisture at the sensor, induced and natural air turbulence around the vehicle, sensor window, and the various motions of the vehicle, i.e., forward motion, roll, pitch, yaw, vibration, etc. Methods, such as image motion compensation (IMC), which have been used to overcome various deleterious effects on sensor performance, are also discussed.

Introduction

Because the aerospace vehicle can and often does provide a hostile environment in which to operate a remote image-forming sensor, most remote sensors cannot be expected to perform as well as they do in a laboratory environment.

This tutorial paper is intended to be an introduction to the more significant aspects of this hostile environment — what effect this environment has on the performance of image-forming sensors and what can be done about overcoming the adverse effects.

The performance of all types of sensors is affected to some degree. The higher the performance, i.e., the better image the sensor is designed to produce, the more likely it is to be degraded by the environment in which it operates. This applies to all types of imaging sensors — photographic, electro-optical, television, line-scan, infrared, radar, and passive microwave.

Evaluation Criteria

The subject of criteria for judging imaging sensor systems is one in which there is considerable controversy today. This controversy is rooted primarily in semantics as well as the problems of making accurate, repeatable measurements involving many different technologies. In this paper, sensor performance will be discussed from the point of view of each of the following parameters.

Resolving Power

Resolving power is defined as the ability of a system to separate closely spaced lines such as those in the MIL Standard USAF resolving power target (see Figure 1). This parameter, which is sometimes loosely referred to as resolution, is related to the spread function* of the system. Resolving power can best be measured with resolving power targets of different contrast.[7] It is usually expressed in line pairs per mm at the detector (photographic film, photocathode, etc.) or at the display. It can also be expressed in terms of line pairs per meter (or foot) at the object although usually it is in terms of feet per line or line pair. (This is often called ground resolution or ground object size resolved.) Quite often, as in TV technology, the number of resolved lines per picture height is used to express resolving power. A line in TV terminology corresponds to a line or a space in photographic terminology and, thus, there are twice as many lines as line pairs. It is also convenient to discuss resolving power in terms of the size of the limiting resolution element or the width of the line at the resolution limit (just resolved) either in the image space or object space. Actually, the limiting resolution element is an area; thus it is the width of the resolved line squared. When the resolving power is not symmetrical, that is it is different in different directions, the limiting resolution element is the area determined by multiplying the width of lines resolved in perpendicular directions. The angle subtended by this just-resolved line at the sensor is another very useful way of describing system limiting resolution. This also is two-dimensional and usually stated in milliradians. Figure 2 is a convenient graph for relating some of the above concepts. It should always be kept in mind that resolving power is a function of the target-to-background contrast.[1,2,4]

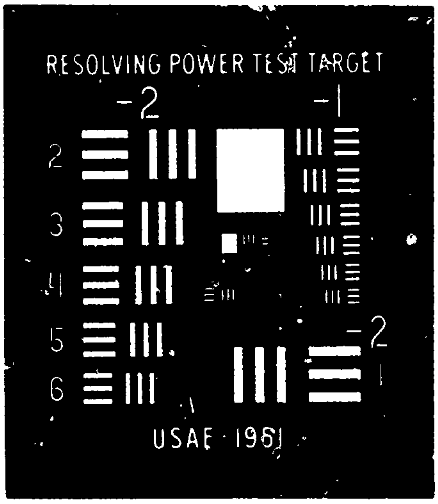

Figure 1. MIL Standard 150 Target

Contrast Rendition

The ability of an imaging system to discriminate between an object and its background is called contrast rendition or contrast discrimination. It is dependent on (1) object-to-background contrast at the detector, (2) the sensitivity of the detector, (3) detective quantum efficiency of the detector, and (4) the number of photons collected by the system (or energy available to the detector). This last factor is dependent on the

*The complex Fourier transform of the line spread function is the optical transfer function or OTF. Its modulus is called the modulation transfer function or MTF and its phase is called the phase transfer function.[1] When the line spread function is symmetrical, the phase shift is zero, the phase transfer function is unity, and the MTF is equal to the OTF. Resolving power is dependent on the OTF, but not in a simple manner; and while it is dependent upon the contrast of the target being resolved, it is also dependent upon the signal-to-noise ratio out of the system. Pure MTF-OTF theory is not concerned with noise.

size of the collecting aperture and on the size of the object one wishes to discriminate. This is another way of saying that contrast rendition is related to resolution and signal-to-noise ratio or that the limiting resolution or resolving power is dependent on the contrast of the target and background. Small-size objects are easier to resolve when object-to-background contrast is high. If the contrast of the object and background is very low, the object must be larger in order to distinguish it from the background.[5,6,7]

Conversion from ANGULAR RESOLUTION to GROUND RESOLUTION

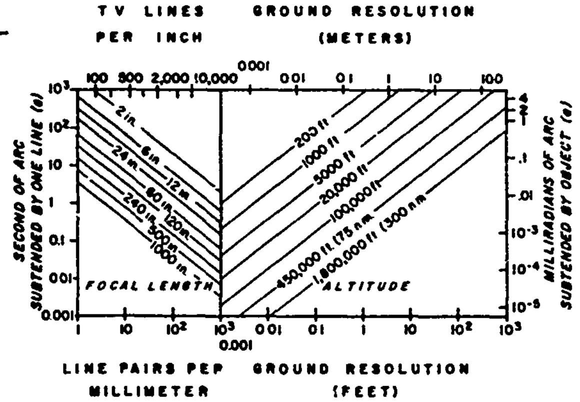

Figure 2

Dynamic Range

The scene dynamic range, i.e., the ratio of the brightest (highest radiance) object in the scene to the darkest (lowest radiance) object in the scene, must be accommodated by the imaging sensor in order to produce a good image. In some cases, such as the sensing of objects on the earth from high altitudes, the path radiance of the atmosphere greatly reduces the scene dynamic range. In other cases, such as imaging objects on the moon, where some objects are in full sunlight and others in deep shadows, the scene dynamic range is very great indeed. Each case creates problems. In the case of low scene dynamic range, it is desirable to utilize "high-gamma" input/output characteristics to stretch the scene dynamic range over the available output dynamic range (see Figure 3). Such systems are usually sensitive to small changes in the environment and tend to exaggerate the "noise". In the case of scenes with a high dynamic range, a "low-gamma" system is employed to compress the scene dynamic range over the available output dynamic range (see Figure 3). If the input/output curve is not linear, this type of system can suffer from poor contrast rendition in the darker and/or lighter portions of the scene. In either case, a high dynamic range output is highly desirable, and anything that degrades the dynamic range of the output reduces the quality of the imagery.

Signal-to-Noise Ratio

The signal-to-noise ratio in imaging systems can best be considered as the ratio of the difference in the object and background signals to the square root of the sum of the squares of the rms fluctuation in the signal of object and background.[2,5,6,7]

Thus

$$(S/N) = \frac{S_O - S_B}{(\sigma S_O^2 + \sigma S_B^2)^{\frac{1}{2}}}$$

This concept can be applied to both the input and output of a sensor, and the detective quantum efficiency (DQE) of the detector/display subsystem is defined as

$$DQE = Q = \frac{(S/N)^2_{out}}{(S/N)^2_{in}}$$

The concepts of signal-to-noise ratio and detective quantum efficiency[5,7] are very useful in understanding the inter-relationship of resolution, contrast rendition, dynamic range, etc., as well as forming a basis for comparing different types of sensors.

INPUT OUTPUT DYNAMIC RANGE

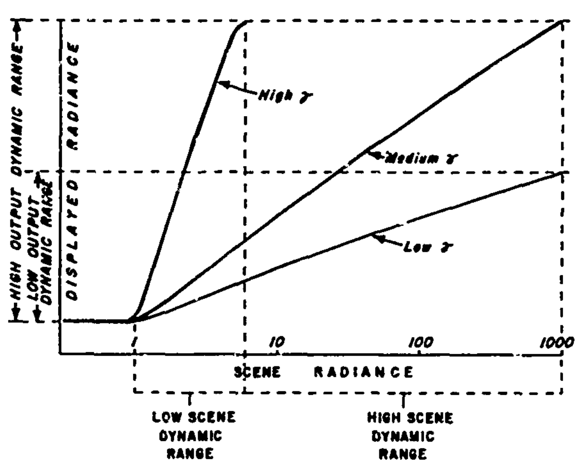

Figure 3

Sensitivity

Sensitivity can probably best be defined in terms of the inverse of the energy per unit area required to produce a specified result. Thus, the more energy a process or device requires, the less sensitive it is. In photographic sensitometry the specified result is usually some quantity derived from the density versus log exposure curve, such as a specified density, a specified threshold gradient, a gradient which is a specified fraction of the average gradient, etc. Maximum resolving power of the photographic material, which is a function of exposure at a specified contrast, has also been used to define sensitivity. Since the output signal-to-noise ratio is also a function of energy per unit area, at any given resolution level, it too has been used to define sensitivity for sensors other than photography. Perhaps sensitivity for all sensors could best be defined in terms of the inverse of the energy per unit area required to produce a specified detective quantum efficiency. With any of the above definitions, whatever increases the output noise and/or reduces the contrast will decrease the output signal-to-noise ratio, and the system will require more energy to produce the same result as before. The system can then be said to be less sensitive. When the detective quantum efficiency remains constant and the sensitivity is increased, the resolving power is lower and the output signal-to-noise ratio is lower for the same size resolution element.

Geometric Fidelity

The accurate depiction of the spatial relationships of a scene is required when spatial or linear measurements are to be made from remotely sensed imagery.[16] Any deviation from an accurate spatial presentation of the scene is called distortion. Images containing low distortion are said to have high geometric fidelity — a property much needed for photogrammetric purposes. When large amounts of distortion are present in an image, the result is often misleading even without attempting to make accurate measurements.

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13. ABSTRACT
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General Appearance

The general appearance of the results of a remote imaging sensor can also be affected by the environment. If care is not taken, unwanted spots, markings, blank areas, streaks, blemishes, unevenness, etc., can result.

Reliability

The environment in which a sensor is used or stored can also have a noticeable effect on the mean time between failure (MTBF) or whether the sensor will even operate at all. Examples of this are obvious to all.

Data Usefulness

The purpose for which the remotely sensed imagery is intended can often be defeated if the environment in which it is used is not carefully considered. For the imagery to be most useful, particularly when photometric or radiometric measurements are to be made, it is of prime importance to calibrate the sensor. Calibration of a sensor can be upset by a different or changing environment. It is often necessary to monitor, with other instruments, the environment in which the sensor operates in order to interpret the results properly. Procedures such as this require calibrating the sensor as a function of the environment. The usefulness of remotely sensed data and the quality of the imagery, as evaluated by the above criteria, are determined to a large extent by the environment within and around the aerospace vehicle which carries the sensor.

Aerospace vehicles have two general characteristics which determine the properties of their environment. These characteristics are vehicle altitude and vehicle motion. Thus, the sensor often is carried in an environment which (1) subjects it to extremes in both pressure and temperature, (2) places it at extreme distances from the objects it must record, and (3) makes it "shake, rattle, and roll". First, we will discuss the properties of the sensor's environment due to this altitude and distance: what degrading effect do these environmental properties have on the imagery, and what can be done to eliminate or reduce this degradation.

Altitude

Object Distance

The most obvious effect of the altitude of the vehicle is that it places the sensor at a great distance from the objects being imaged. This usually results in a small-scale image, and many important objects of relatively small size may be unresolved (see Figure 2). To obtain higher angular resolution, the system designer can resort to large, long focal length optics (large focused antennas for microwave), and this results in less coverage for a given image format. Of course, the simplest way in which to get good "close-up" (large-scale) imagery is to get "close up", but this often presents problems such as image motion and, certainly, less coverage. There is always a trade-off between angular resolution and angular coverage. The optical collector must also be large in diameter for two reasons: (1) to collect enough energy to be compatible with the sensitivity of the detector (f number), and (2) to obtain small angular resolution as shown in the famous Rayleigh criterion

$$\alpha = 1.22\,\lambda/D$$

where α = angular resolution in radians
λ = wavelength
D = diameter of collector

For practical radar targets, we can resolve better than the Rayleigh criterion implies by taking advantage of other target parameters and sophisticated data processing techniques.''

The resolving power of an imaging sensor is also related to the sensitivity of the detector. In general, when the detective quantum efficiency remains constant, a highly sensitive detector, such as "fast" film, has poor resolving power. High-resolution film has a low sensitivity. When there is plenty of energy available, as in bright daylight, high resolving power systems are more feasible.

Another problem (when using active systems such as radar) resulting from operating at a great distance from the scene is that the energy requirements increase as the area covered increases. This is often not just a simple quadratic relationship. The power or energy required can often increase at a rate greater than the square of the distance, particularly if one attempts to maintain equivalent ground resolution over a greater area.

Temperature

The temperatures to which a sensor is subjected at high altitudes can also create problems. Both high temperature, due to solar radiation and inadequate cooling, as well as low temperature can affect the performance of an optical system. Temperature also affects the sensitivity of the detector. Temperature gradients within a high-resolution optical system can often decrease the performance considerably and in a manner not easily amenable to compensation such as changing the focus.

High temperature is particularly troublesome with infrared detectors, which must be cooled to very low temperatures to obtain the required sensitivity, contrast rendition, and signal-to-noise ratio. Not only should the temperature at the detector be extremely low, but any material in the optical path, which the detector "sees" (such as optics, windows, or objects near the aperture), should also be cool in order to reduce "background thermal noise". Any increase in thermal noise can result in image degradation consisting of poor contrast rendition, loss of dynamic range, or loss of resolving power at low contrast. Photoconductors in general, including those responsive in the visible and near-visible region of the spectrum, operate more efficiently with less dark current when cooled. Photographic film, on the other hand, requires that the temperature be above a certain minimum (usually about 30°C) to operate efficiently and not lose sensitivity. Photographic materials, when stored at high temperatures, become fogged. The fog is somewhat analogous to dark current in photoconductors. Ideally, photographic material should be stored at low temperature and exposed (either informational or post exposure)" at moderately high temperature.

Pressure

Low atmospheric pressure can create problems. The focus of an optical system is upset due to the change in index of refraction of the atmosphere. If part of the system is pressurized, the pressure can create physical distortions of optical components, such as windows, and cause degraded imagery. Low pressure can also result in the outgassing of solvents in photographic film, altering its sensitivity. This has been observed particularly with false-color IR Ektachrome, in which the color balance of the three layers was noticeably upset. Outgassing at low pressure, coupled with low humidity and low temperature, can also result in brittle film and camera malfunctions due to torn film. Moving parts of sensors must also be properly lubricated for low temperature and pressure to prevent malfunction. Low pressure also increases the probability of arcing in electronic systems utilizing high-voltage components.

Humidity

Humidity is another culprit that can be troublesome in more ways than one. Not only is low humidity a problem in outgassing of photographic film when coupled with low pressure, but the same combination of environmental factors increases the problem of static electricity, which results in unsightly marks on photographic film (see Figure 4). To eliminate static marks on film, care should be taken to make proper use of anti-static coatings on moving parts of the film transport and on the film itself. Attention should be given to suitable grounding to prevent static buildup. High humidity, of course, can cause moisture precipitation on optical components such as mirrors, lenses, and windows (particularly if they are cooled). This moisture, even when hardly visible to the human eye, can be extremely harmful in reducing dynamic range and resolving power at low contrast. This lowering of contrast often results in a lower output signal-to-noise ratio. Moisture condensation on improperly potted electronic components can also result in poor imagery as well as decreased MTBF, i.e., less reliability. Condensed moisture, if subsequently exposed to very low temperatures, will often result in freezing and complete malfunction of moving parts of an imaging sensor.

Figure 4. Static Marks

Correcting for Temperature, Pressure, and Humidity Effects

The best way to minimize the problems resulting from extremes of temperature, pressure, and humidity is to inclose the sensor in a properly climatically controlled environment. This will include, for best results, heaters, air-conditioners, desiccants, etc. Extreme temperature gradients should be avoided. Implied in the above is, of course, a window which must be of adequate optical and physical quality to meet the conditions. This window, IRDOME (infrared) or RADOME (radar), should be treated as part of the optical or electromagnetic sensor system with respect to its quality, spectral transmission, etc. In high-resolution optical systems, turbulent air flow near the aperture (entrance pupil) should be avoided.

Radiation

The radiation encountered at high altitudes is the final altitude-related environmental problem to be considered. The sun is perhaps the chief culprit as far as radiation is concerned. Not only is it the source of much of the particle radiation existing in the Van Allen Belts, but it is also a source of gamma and X-radiation at higher altitudes. The primary radiation of the sun can seriously degrade images when the sensor is not properly shielded from direct or near-direct impingement. Improper shielding will result in flares, ghosts, and veiling glare, not to mention permanent damage to the detectors (when the sun is imaged directly). It has been reported[9] that the color television camera on Apollo 12 failed because of direct exposure to the sun or reflection of the sun from the foil covering of the landing module. The sun's radiation can also cause heating of the sensor compartment.

Particle radiation such as alpha particles, beta particles, and neutrons can add to the base fog of photographic film. Normally, though, even with photographic film which integrates exposure over a long period of time, the effect does not cause serious trouble. Gamma rays and X-rays are potentially more serious. Even here the photographic film is usually no more sensitive to a given dosage than is man. Any environment, which is deemed safe for a human, is safe for photographic film![10] After all, a very sensitive dosimeter is made from special photographic film. Particle, X-ray, and gamma radiation produce even less effect on the final image in electro-optical systems since the photoemissive and photoconductive detectors used in these systems do not integrate exposure during storage.

Electrical and electromagnetic interference can also result in radiation which sometimes produces spurious signals that interfere with or mask the desired result. Imagery, suffering from this type of interference, will sometimes show false, unwanted data in the form of streaks, distortions, scrambled images, or random noise. Photography, of course, is not subject to this type of interference. However, the electrical components in a photographic sensor can be the source of interference for other sensors. Electrical interference is most pronounced in electro-optical and infrared sensors where high-gain amplifiers are employed. Radar systems, which utilize a broad bandwidth in the electromagnetic spectrum, are also highly susceptible to interfering noise. The solution to electrical interference is attention to details in electrical noise suppression and proper shielding of sensitive components.

Vehicle Motion

The motions of an aerospace vehicle are many and complex. They include not only the velocity of the vehicle but also externally induced motions resulting from the interaction of the vehicle and its environment. There are also vehicle motions caused by such things as the propulsion system.

Indirectly, the forward motion of an aircraft can create induced air turbulence and a shock wave, particularly at high speed. The induced air turbulence at the boundary layer, particularly in the transonic region, can degrade the performance of a high resolution sensor.[11-17] The optical inhomogenities, created at the sensor window, result in reduced resolving power. To avoid this, the window should be located at a position in the aircraft where laminar air flow exists in the boundary layer.

Shock Wave

When the shock wave occurs in the far field of an optical sensor and is in a relatively steady state, the resulting imagery can be of good quality if the intersection of this shock wave with the ground is not in the picture.[11] Figure 5 is an example of a picture made with a wide-angle mapping camera. The intersection of the shock wave with the ground creates a sharp discontinuity in the picture. When this picture is used as one of a stereo pair, with the other made either before or after the shock-wave line, the three-dimensional model shows a 20-foot cliff in the corn field. When the shock wave occurs in the near

field of an optical system (at or near the entrance pupil, particularly in an unsteady state), the resolution of the resulting imagery can be degraded. To avoid shock-wave problems as well as heating effects of supersonic flight at low altitude, it is best not to perform mapping photography at transonic or supersonic speeds.

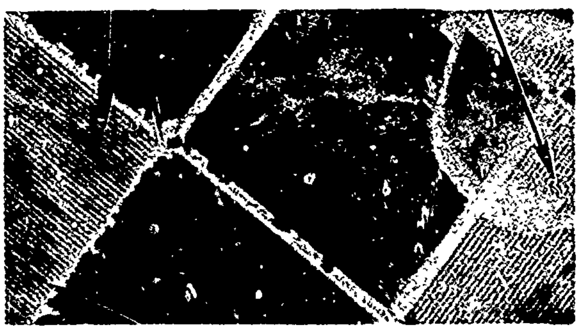

Figure 5. Shock Wave on Ground

Heating Effects

At high air speeds, heating effects (particularly window heating) can create problems such as those discussed above on the subject of temperature effects. In addition, temperature gradients in the window cause geometric distortion, of significance to photogrammetrists. As one would expect, infrared sensors will suffer most from warm windows. Air-conditioning and cooling techniques are the obvious solution to this problem. Removing the window entirely may result in compounding other environmental problems.

Sensor Motions

Vehicle motions, which induce sensor motions resulting in image smear, are perhaps the most serious obstacles to high resolution[6,31] which a sensor has to overcome. The following types of motion must all be considered carefully in designing a high-resolution, image-forming sensor subsystem:

1. Forward Vehicle Motion
2. Roll
3. Pitch
4. Yaw
5. Buffeting
6. Vibration
7. Sensor-Induced Motions.

The severity of the effects of roll, pitch, and vibration is shown in Figures 6 and 7. Figure 6 is a plot of vibration amplitude versus vibration frequency; lines of constant acceleration (g) are shown. The shaded region includes most vibrations, which influence sensor quality, likely to be found in aerospace vehicles. Figure 7 is a plot of maximum roll and pitch rate (in milliradians per second) as a function of frequency. The first shaded region includes roll and pitch motions of most aerospace vehicles. The second shaded region is a re-plot of Figure 6 and shows the effective maximum angular rate of vibration, assuming that the vehicle vibration is transmitted directly to an optical system having a 12-inch optical length and that the two ends are vibrating out of phase. The shaded regions in Figure 7 overlap, which indicates that high roll and pitch rates can result in sensor motion similar to that due to low vibration frequencies. The results of these types of motion on the imagery will be discussed later.

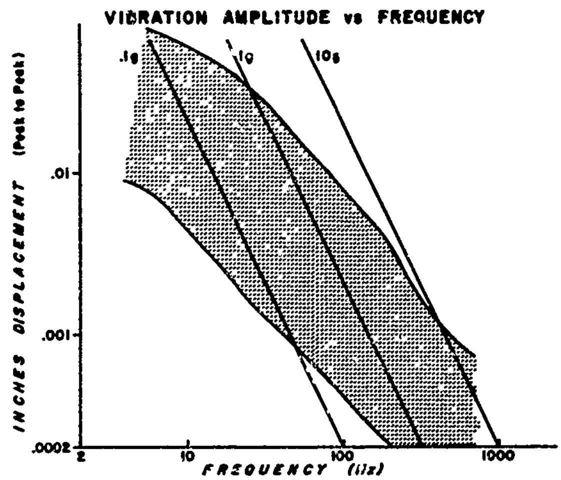

Figure 6

Forward Image Motion

Forward image motion smear is one degrading effect which we can correct, at least partially.[22] In fact, most sensors depend on the forward velocity of the aerospace vehicle to provide the coverage in the direction of flight. Many sensors scan perpendicularly to the flight line, and the aircraft forward motion provides a means of scanning in the direction of flight.

Image smear can best be anclyzed in terms of angular resolution. The image can be said to have an angular velocity in the focal plane which is measured in terms of V/H, where V is the sensor velocity and H is the object distance or altitude. V/H is measured in radians per second. Figure 4 is a plot of the V/H, as a function of altitude, in a range of aerospace vehicles when the sensor is pointed downward.

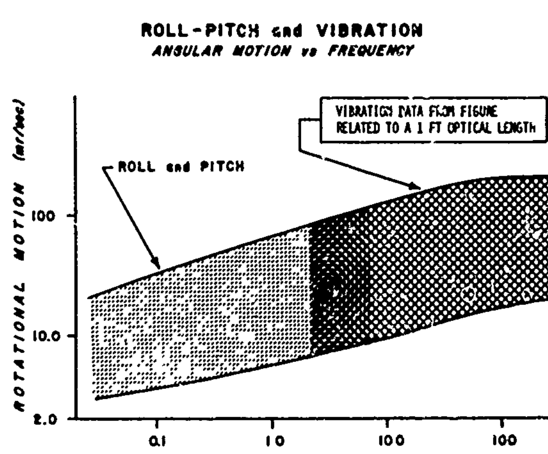

Figure 7

To compute the limiting angular resolution α_M due to forward image motion, one need only multiply V/H by t (the integration time, exposure time or dwell time of the sensor) and by δ (the IMC error). Thus:

$$\alpha_M = (V/H)\, t\, \delta$$

In addition to image smear created during exposure time, there is often a loss of resolution due to "lag" or image "sticking". This can occur, for example, in the case of photoconductive sensors such as the vidicon television camera tube when some stored charge from previous frames remains on the target, out of register with the new image being read out by the electron beam.

If one assumes that the spread function at the image plane due to this motion is Gaussian in shape and that the limiting angular resolutions due to the optics and detector are also Gaussian, then one can write the following approximate expression for the limiting angular resolution of the system:

$$\alpha_S = (\alpha_O^2 + \alpha_D^2 + \alpha_M^2)^{\frac{1}{2}}$$

where α_S = angular resolving power of system
α_O = angular resolving power of optics
α_D = angular resolving power of detector/display
α_M = angular resolving power due to motion or image smear

To reduce α_M to the lowest practical value, one can reduce t by utilizing very sensitive detectors. In the case of photography and television, this requires more sensitive detectors which, in turn, usually have less resolving power so that α_D becomes large. The exposure time t is very short in many line-scan devices where the dwell time of the detector on the scene is measured in microseconds. The size of the detector and, thus, the angular resolution of the detector/display portion may, however, be made large to increase sensitivity. The dwell time of this type of sensor cannot be shorter than the detector response time constant for efficient operation. Mechanical problems of providing a high scan rate at high V/H may also result in an inadequate scan pattern with gaps in the area scanned. Larger detectors (poorer angular resolution) or multiple detectors will help solve this problem.

Another way in which image smear may be reduced is by compensating for the image motion with some type of IMC (image motion compensation) device.[22] Moving sensors, film, mirrors, mounts, prisms, and lenses have all been used at one time or another to compensate for forward image motion. Some of these principles are illustrated in Figures 8 and 9. The IMC principles illustrated in Figure 8 show four methods of providing a compensating motion:

(a) Rotating the camera in its mount to track the moving scene.

(b) Moving the recording film at the same velocity as the image motion.

(c) Rotating two prisms about the optical axis to vary the total refracting angle at the proper rate and in the proper direction.

(d) Moving only the lens of the camera at the same velocity as the ground.

Figure 9 shows 3 additional methods:

(a) Moving a flat optical side of a liquid prism to provide variations in refracting angle (similar to Figure 8, c).

(b) Electronically moving an electron image with the same velocity as the image motion.

(c) Rotating a mirror or mirrors in an optical system to track the moving scene.

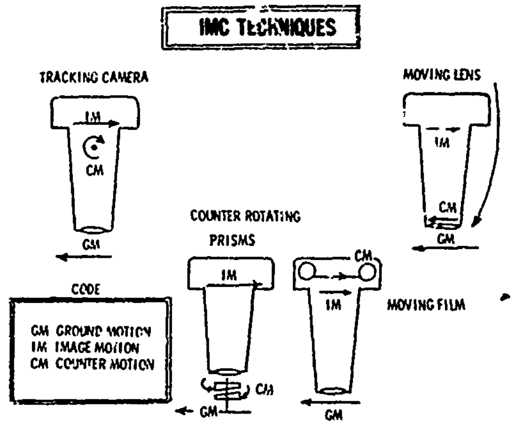

Figure 8

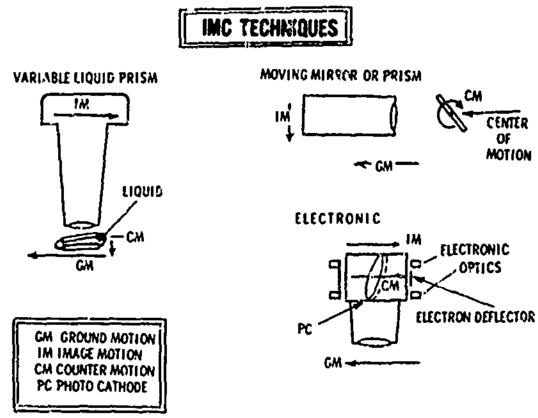

Figure 9

Figure 10 is a photograph made with a 6-inch focal length lens without IMC, while Figure 11 is the same scene photographed utilizing a moving-film technique wherein the film was moving at a rate of 4.0 inches per second.

The input signal required for the operation of the devices illustrated in Figures 8 and 9 can come either from previous knowledge, or independent measurement of the vehicle velocity and the distance from the scene, or it can be sensed by a V/H sensor directly.[23-30] Figure 12 illustrates three principles that form the basis for V/H sensors which have been employed. They are:

(a) Scanning the ground with a detector in back of a multiline ("picket fence") reticle at a focal distance F from an imaging lens. This produces a signal s proportional to the velocity. Then

$$V/H = f(s, F)$$

(b) Tracking the ground with an optical tracker, which can be one of several types, and sensing the angular tracking rate ω, then

$$V/H = F(\omega)$$

(c) Sensing the scene twice with optical sensors which record an analog signal of the scene as viewed from two directions at two different times. The first record is stored and correlated with the one sensed at a later time. The time t between the first look and the second look at the same scene and the angle β between the sensors provide the V/H:

$$V/H = f(t, \beta)$$

Various combinations of the above principles have been used, including a movable grid (similar to (a)) combined with (c), as well as single-slit scanning to produce the video correlation signal. Many different correlation techniques have been applied. Some yield not only V/H but its direction, which in turn yields yaw angle. The Correlatron tube has also been applied.

Figure 10. Photograph Without IMC

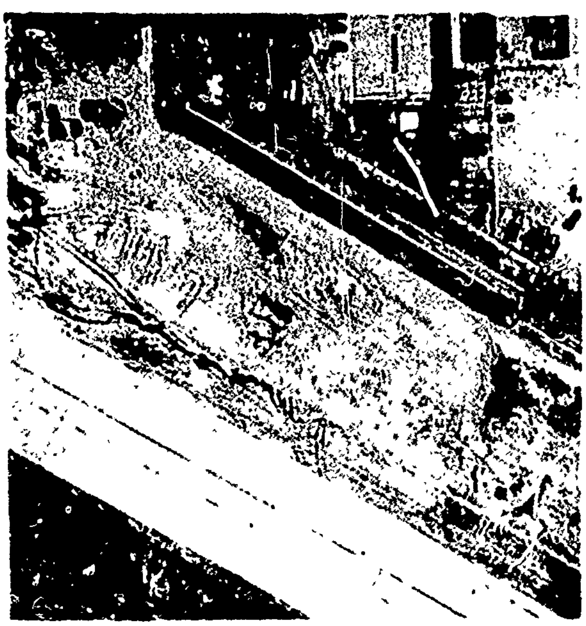

Figure 11. Photograph With IMC

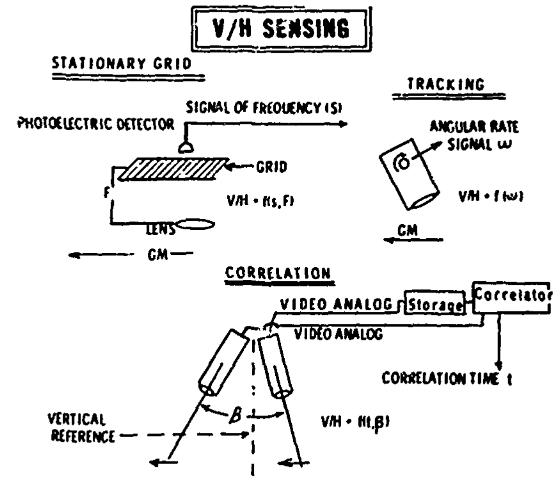

Figure 12

To obtain some idea of the expected magnitude of V/H, refer to Figure 13. In this figure, the conventional flight spectrum is depicted but, instead of plotting velocity as a function of altitude, we have plotted the ratio V/H as a function of altitude with diagonal lines representing velocity. It can be seen from this plot that V/H can vary, depending on vehicle and flight regime, from less than 0.01 radian per second to approximately 6 radians per second.

All IMC subsystems have limitations in their ability to compensate perfectly for forward image motion. This limitation is expressed as IMC error δ and is the result of inaccuracies in measuring V/H and inaccuracies in producing the required IMC. One of the chief problems is that in any given picture or display V/H can seldom be considered constant over the whole format. This is particularly true when the scene is imaged at other than a constant scale factor, due either to distortion of imaging in a forward- or side-looking oblique direction. In some vertical panoramic-type imaging devices or side-looking frame-type oblique installations, a form of variable IMC can be employed in which different amounts of IMC are used in different parts of the image. Variations of terrain height within the scene also introduce IMC errors.

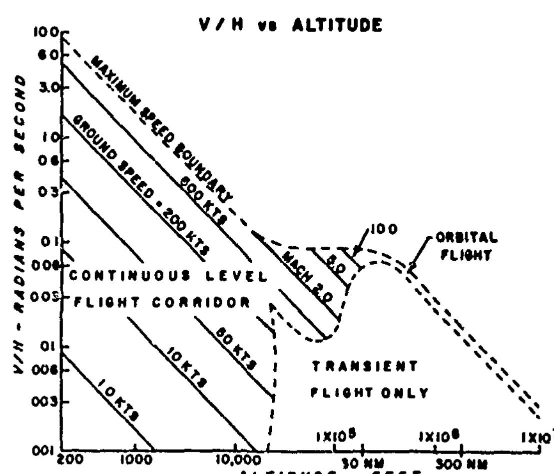

Figure 13

Roll, Pitch, and Yaw

Roll, pitch, and yaw of the aerospace vehicle further complicate the V/H problem and, with some sensors, introduce their own unique problems. For example, line-scan sensors, either of the electro-optical scanning type or strip camera type, will produce, in the presence of roll, distorted images of the scene (see Figure 14). Pitch rate will introduce a varying forward image smear; yaw, unless corrected by adjusting the "crab angle", will introduce a vector of image motion which is not parallel to the compensated motion.

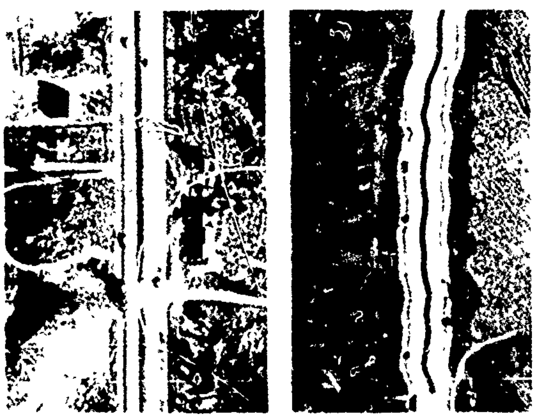

Figure 14. Roll Distortion

High rates of pitch, yaw, and roll will introduce image smear in a manner similar to high-amplitude, low-frequency vibration (see Figure 7).

STABILIZED MOUNTS

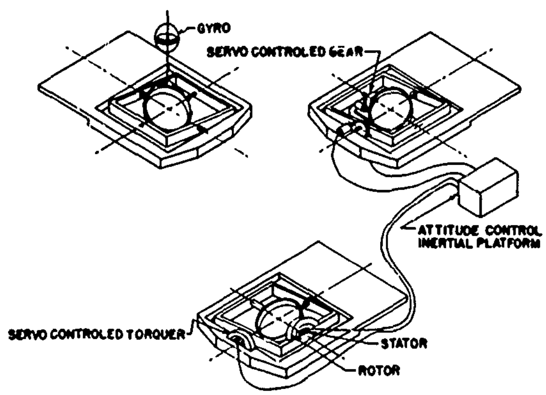

Figure 15

Roll, pitch, and yaw of aerospace vehicles can often be prevented from degrading the imagery of remote sensors by the use of stabilized mounts.[12] Several types of stabilized mounts are illustrated in Figure 15. Stabilized mounts usually depend upon some type of inertial platform for their control inputs. Some stabilized mounts have been controlled directly by the inertia of a large gyroscope. An excellent type of mount is the torquer mount in which the sensor package is mounted on gimbals and the gimbals are controlled by electromagnetic forces. The internal part of the torquer performs like the rotor of a d-c motor. The external part of the torquer acts as the stator (see Figure 15). Stabilized antennas are also utilized in high-resolution radar systems in addition to electronic stabilization. Both techniques require inputs from a high-quality inertial platform. Stabilized mounts provide another useful function for mapping cameras, that is, maintaining verticality of the camera to reduce the necessity for laborious data reduction during map compilation.

Buffeting

Buffeting can be thought of as a severe form of roll, pitch, and yaw produced in a more erratic manner. It is the result of the vehicle's reaction to natural air turbulence. When this turbulence is very severe, stabilized mounts cannot adequately cope with it.

Vibration

Vibrations within the vehicle structure and sensor itself are often transmitted in such a manner as to create an image smear during the exposure or integration time.[11] The relative motion of detector and image during this exposure time is not as simple as in the case of pure linear motion created by the forward motion of the vehicle in absence of yaw. The complex nature of the vibrations involved is often difficult to analyze. When the exposure time is short and the amplitude of the resulting sensor vibration is great (usually the case with low-frequency vibration), the resulting vector of motion involves less than one cycle of vibration. This creates an effect on the sensor which is somewhat like that caused by roll, pitch, or yaw (see Figure 16). When the resulting sensor vibration is high-frequency, low-amplitude and with relatively long exposure time, the resulting image smear can be two-dimensional and its magnitude is determined by the amplitude of the image vibration (see Figure 17), which may be more or less than the impressed vibration.

LARGE AMPLITUDE LOW FREQUENCY SMEAR

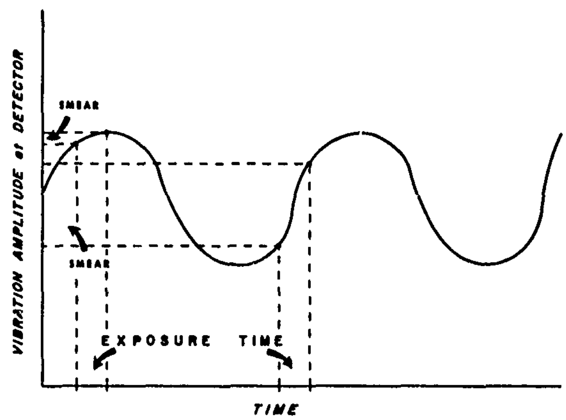

Figure 16

The sources of vibration can be numerous. Some common sources are vehicle engines, propellers, interaction of wind on vehicle surfaces (which causes skin motions and air frame flexures), acoustical vibration, as well as internal sensor mechanical motions resulting from moving parts of the sensor. Even the body motions or heart beat of an astronaut astronomer could possibly affect the resolving power of a very high resolution telescope in orbit. The exact manner in which vibrations are translated into image smear is largely a function of sensor design and sensor mounting. Sensors involving mirror designs are often more susceptible to vibration because of the amplitude doubling effect of reflecting surfaces. If mirrors are not mounted properly, flexures of their surface can degrade optical quality.

Mounting sensors at their center of gravity is the recommended operating procedure, and the use of passive vibration isolator mounts of many different types has long been standard practice.[33,34,35]

LOW AMPLITUDE HIGH FREQUENCY SMEAR

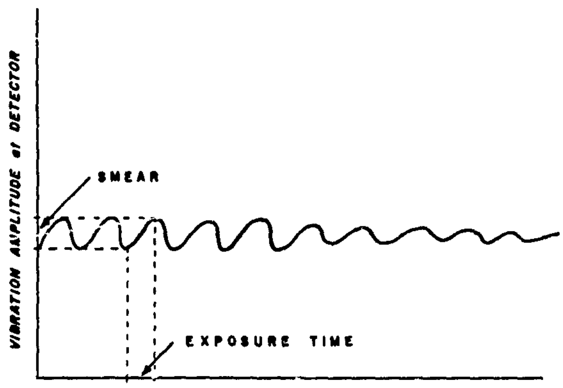

Figure 17

Passive isolators, however, have their limitations. They can only be designed to operate best over a rather limited frequency range. Active vibration isolators are now being studied.[36] These active isolator systems sense the motion by means of accelerometers and apply a countering force through either electric or pneumatic actuators. Active optical means, similar to IMC devices, have also been employed. These apply a correction to the light path through moving mirrors* or by changing the power of liquid prisms**. Small gyroscopes have been used as sensors for determining the amount of correction required. In electro-optical systems, the correction required can be applied by deflecting an electron beam or electron image***. These optical, active techniques have proven successful when dealing with small-aperture systems, but they have limitations for some very high resolution, large, optical systems.

Conclusions

In spite of the many pitfalls, problems, and difficulties outlined**** in this paper, remarkably high-quality imagery has been obtained with a wide variety of remote imaging sensors. We have all seen examples of this high-quality imagery obtained under adverse environmental conditions. We seldom see the failures.

To provide more successes and fewer failures, remote sensing systems must be designed to be compatible with the aerospace environment in which they are to be used. The required quality of the imagery should be dictated by the purpose for which the information is collected.

Detailed consideration should be given to the selection of the most suitable aerospace vehicle. During design, analysis, and testing of the remote sensing subsystem, attention must be given to the following details:

(a) Location, on and in the vehicle, of the sensor components
(b) Sensor mounting methods
(c) Image motion compensation (IMC)
(d) Vibration isolation or control
(e) Temperature and humidity control
(f) Pressurization
(g) Sensor calibration
(h) Auxiliary data recording.

Finally, the most appropriate time, altitude, and vehicle velocity at which to perform the mission are prime factors to consider. Careful consideration of the above factors will insure successful results.

* Mark Systems, Inc.
** Dyna Lens, Dyna Science Corp.
*** Itek Corp. & others
**** For a more complete discussion of this subject see the references in the bibliography.

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